# Complete Set of Deuteron Analyzing Powers for *dp* Elastic Scattering at Intermediate Energies

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# Nucleon-Deuteron Scattering

a good probe to study the dynamical aspects of 3NFs.

✓ Momentum & Spin dependence
✓ Iso-spin dependence : only T=1/2

## Direct Comparison between Theory and Experiment

- Theory : Faddeev Calculations
  Rigorous Numerical Calculations of 3N System

| 2NF Input | 3NF Input | 2NF & 3NF Input |
|---|---|---|
| • CDBonn<br>• Argonne V18 (AV18)<br>• Nijmegen I, II, 93 | • Tucson-Melbourne<br>• Urbana IX<br>etc.. | • Chiral Effective Field Theory |

- Experiment : Precise Data
  - $d\sigma/d\Omega$, Spin Observables ($A_i$, $K_{ij}$, $C_{ij}$)

## Extract information of Three Nucleon Forces.

# Three Nucleon Force (3NF)

## 1957 Fujita-Miyazawa 3NF

**Prog. Theor. Phys. 17, 360 (1957)**

- 2π-exchange 3NF :
  - Main Ingredients :
    Δ-isobar excitations in the intermediate

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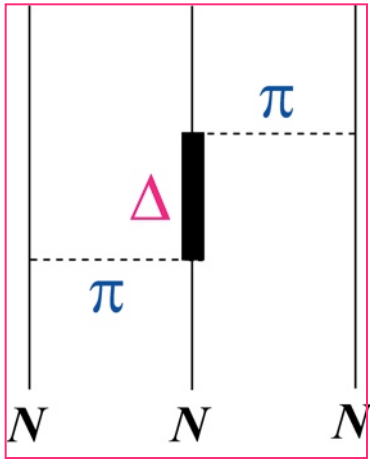

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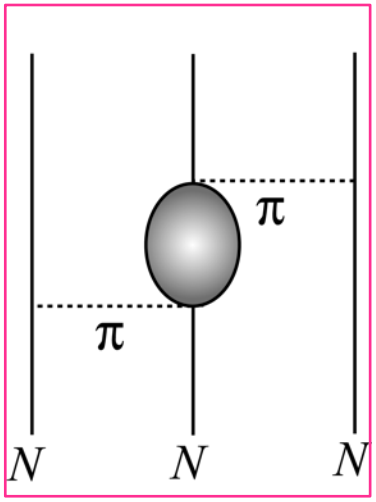


- Tucson-Melbourne (TM)
- Urbana IX
- Brazil, Texas etc…

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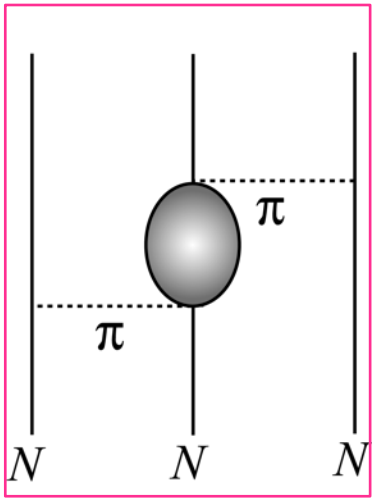


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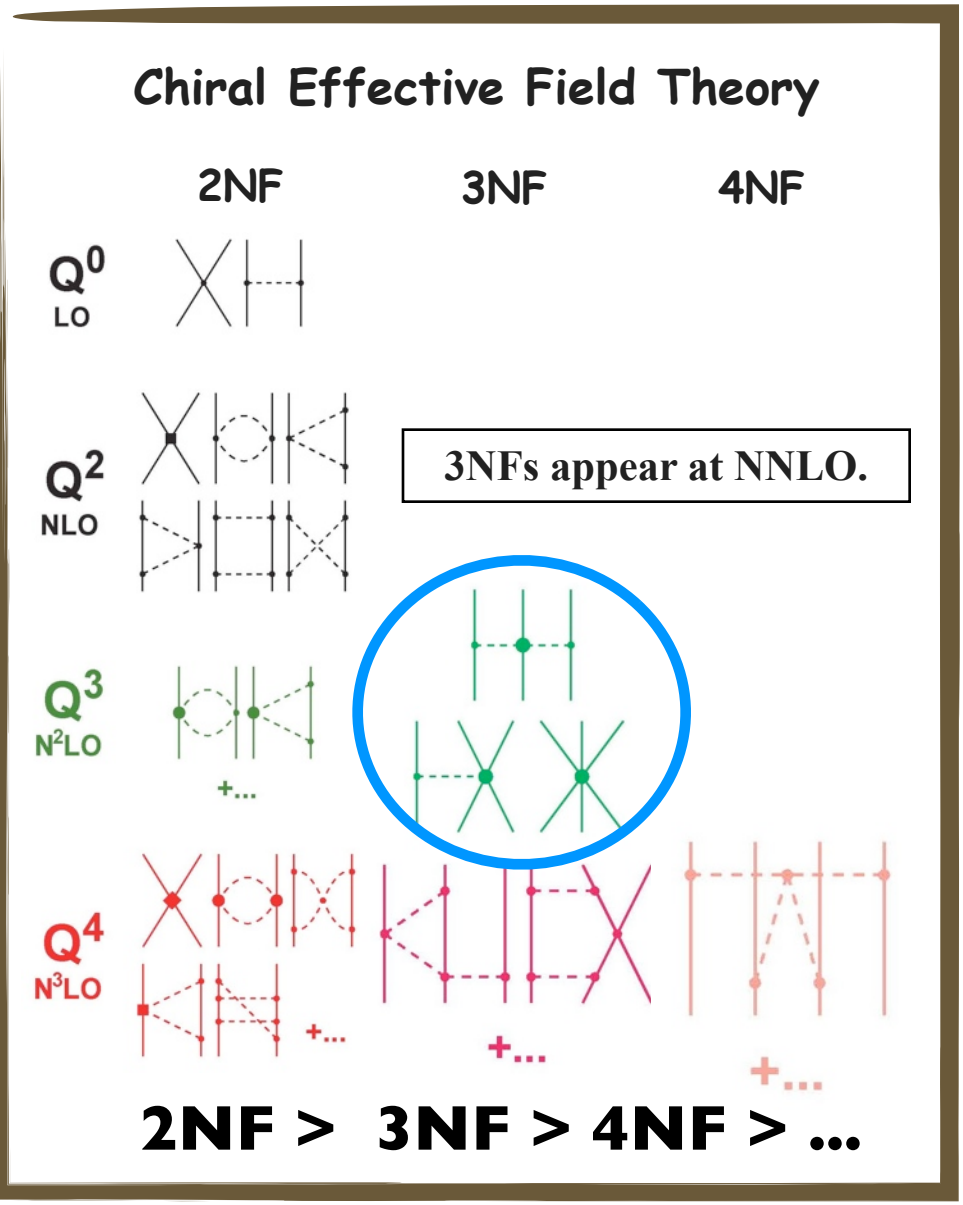
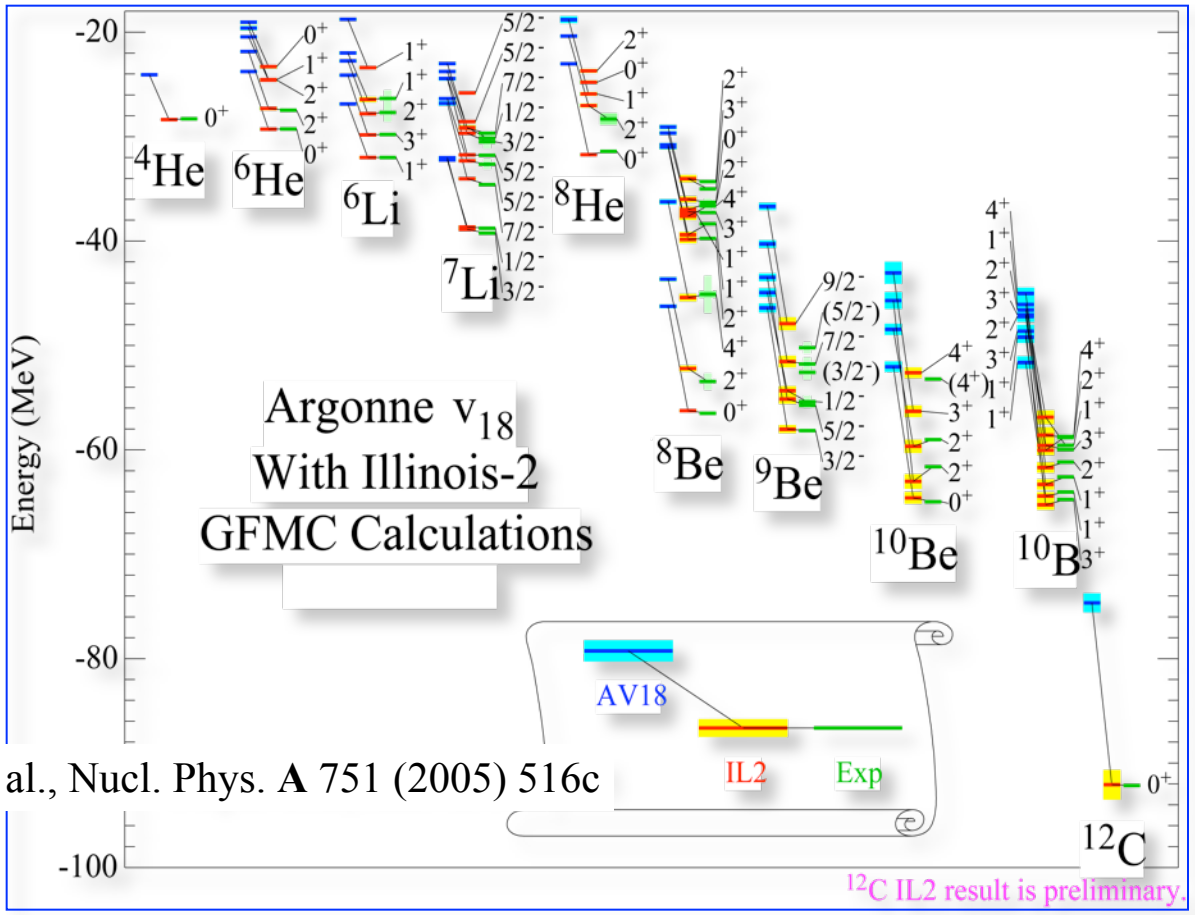


# Where can we find 3NF effects ?

## Ab Initio Calculations for Light Nuclei (A < 12)

- **Green's Function Monte Carlo**
- **No-Core Shell Model** etc..




Pieper et al., Nucl. Phys. **A** 751 (2005) 516c

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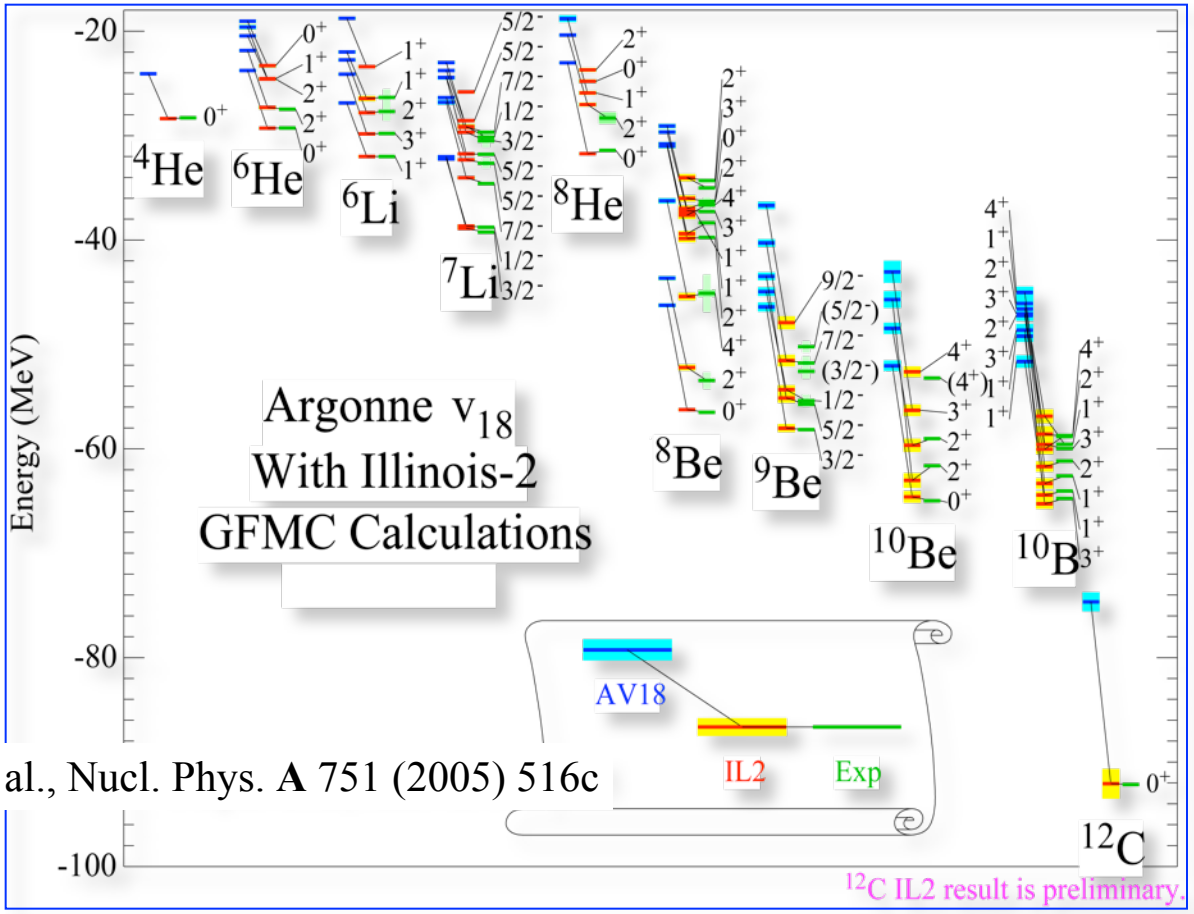
•2NF provide less binding energies

•3NF : well reproduce the data

**IL2 3NF (Illinois-II 3NF)** :
2π-exchange 3NF
+ 3π-ring with Δ-isobar

•3NF Effects in B.E.
- 10 ～ 25 %
- attractive

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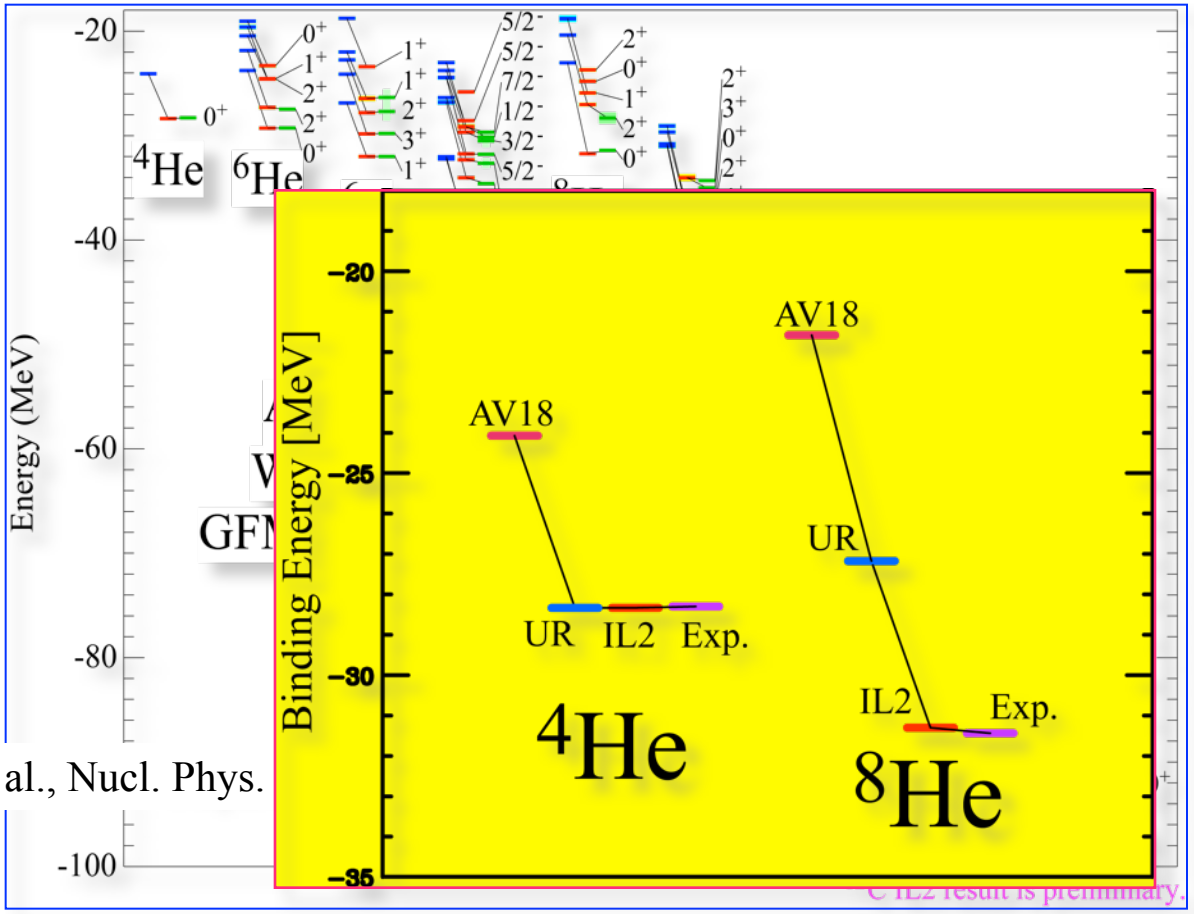


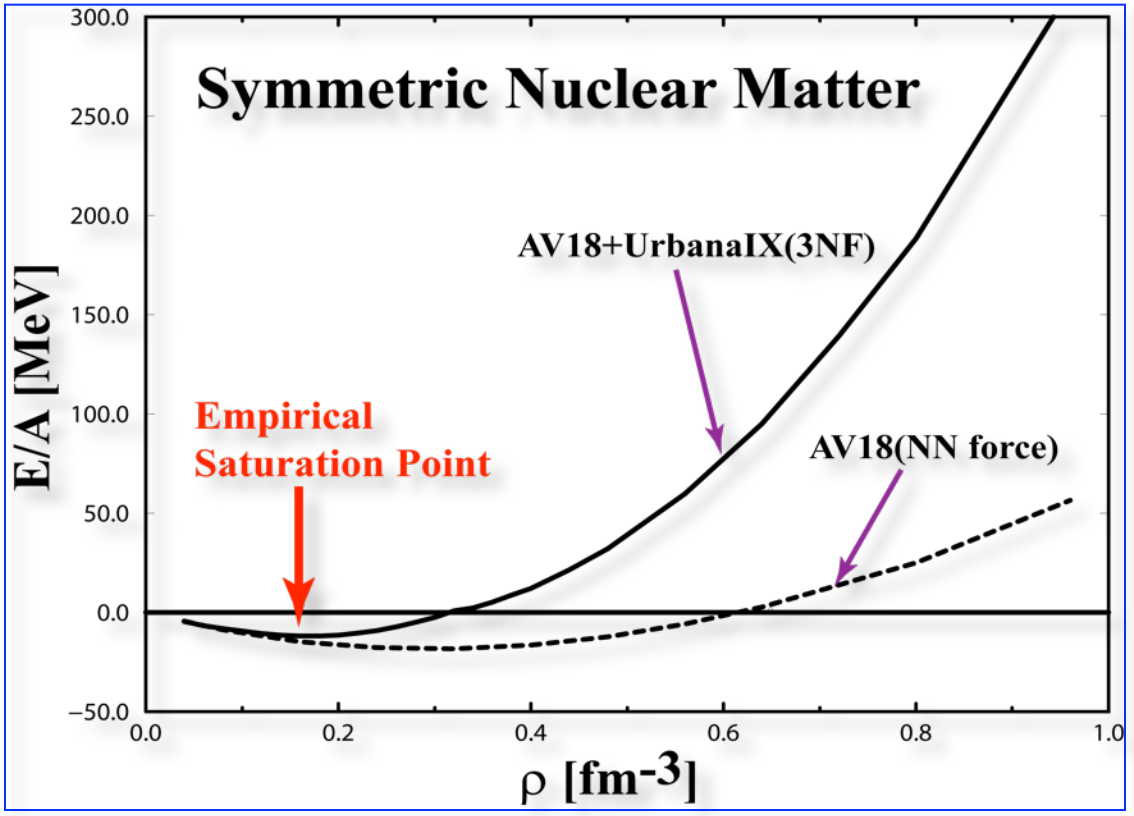

Pieper et al., Nucl. Phys.

# Where could we see 3NF effects ?

## Equation of State for Nuclear Matter

- All NN potentials (AV18, Nijmegen I,II, CD Bonn) provide larger saturation point of Nuclear Matter.

- 3NF
  - shift to the empirical saturation point
  - significant at higher density

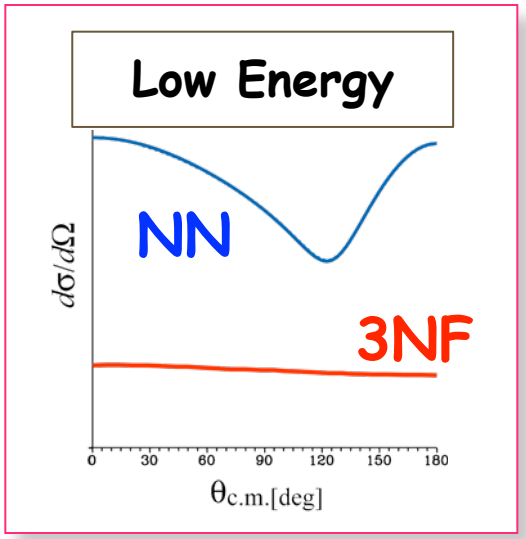


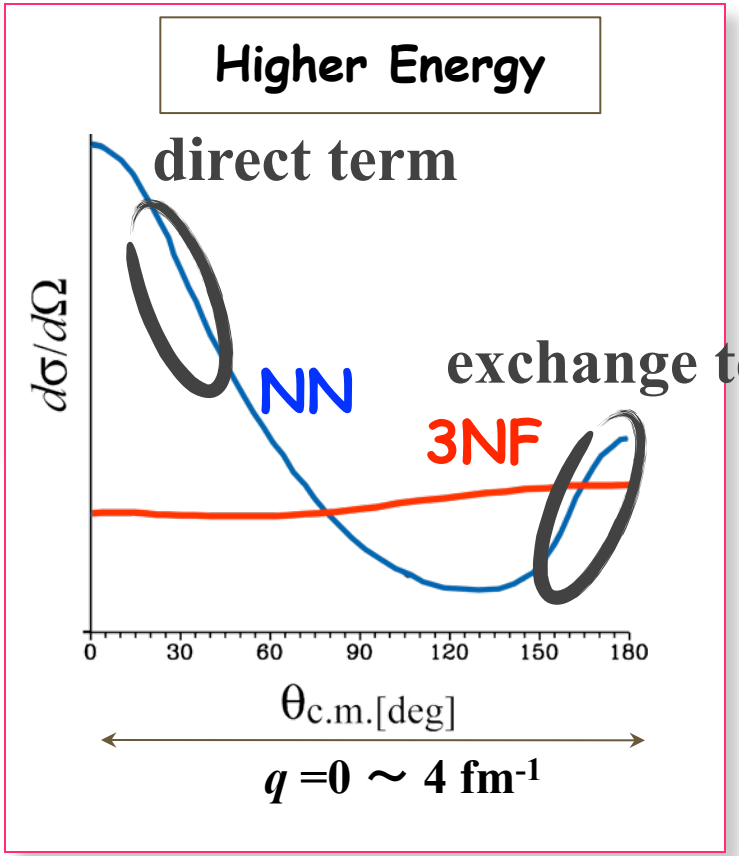

A. Akmal et al., PRC 58, 1804('98)

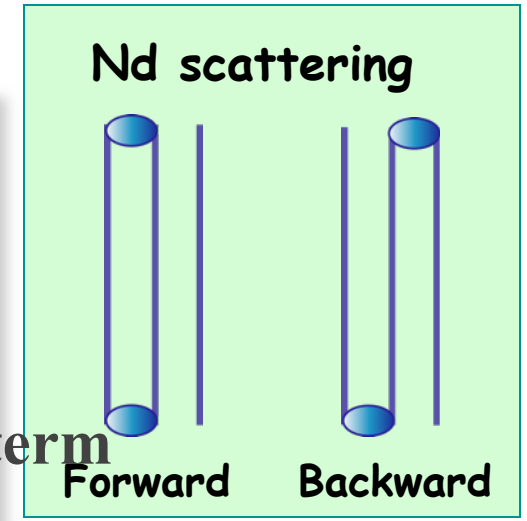
# Where is the Hot Spot for 3NF Effects in Three Nucleon Scattering?

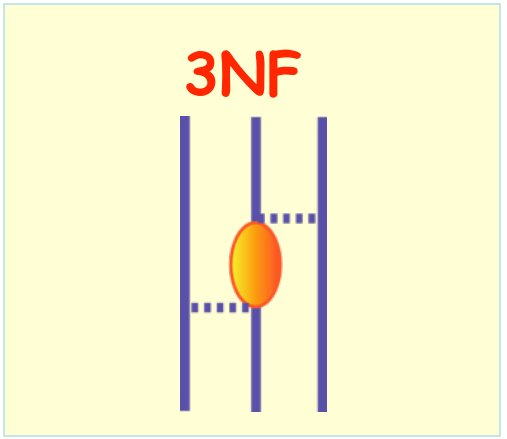
**Predictions by H. Witala et al. (1998)**

**Cross Section minimum for Nd Scattering at 100-200 MeV/A**



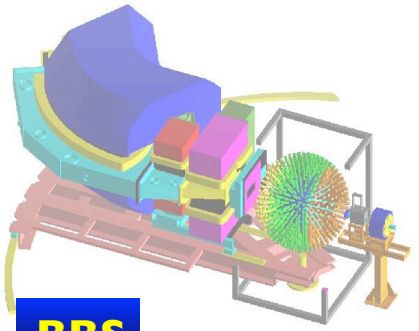



# Facilities

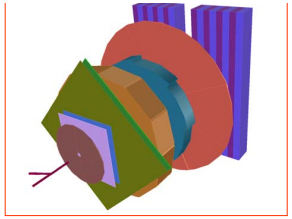
## RIKEN

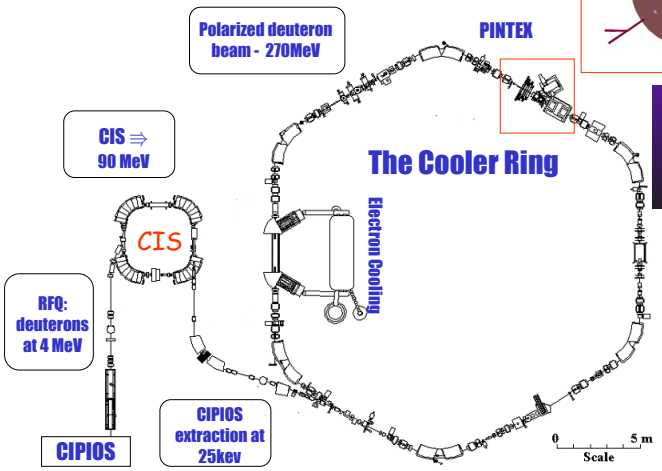

## BINA & SALAD

## KVI



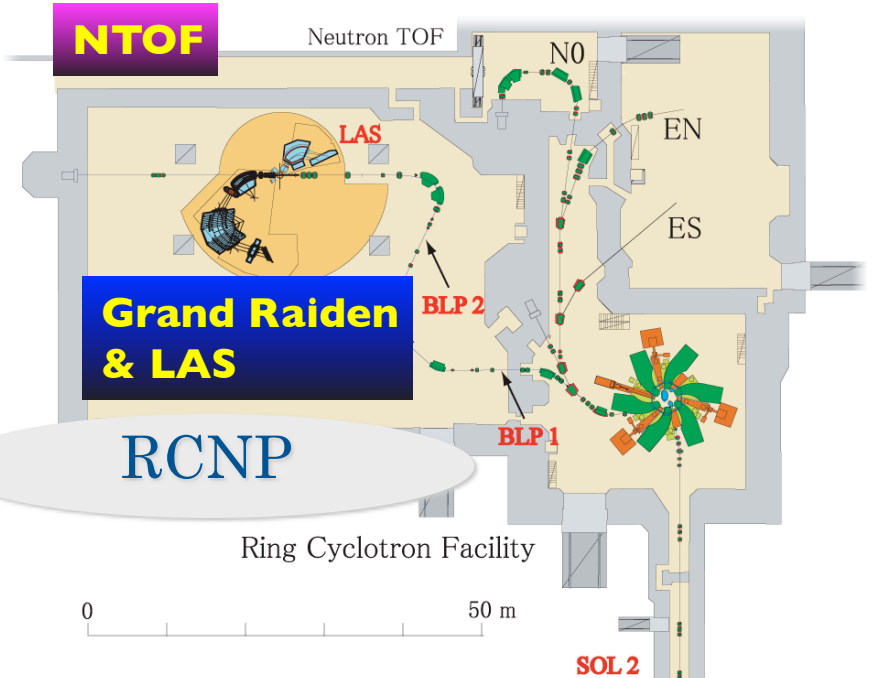

## IUCF






**Cooler Ring + PINTEX**

## NTOF



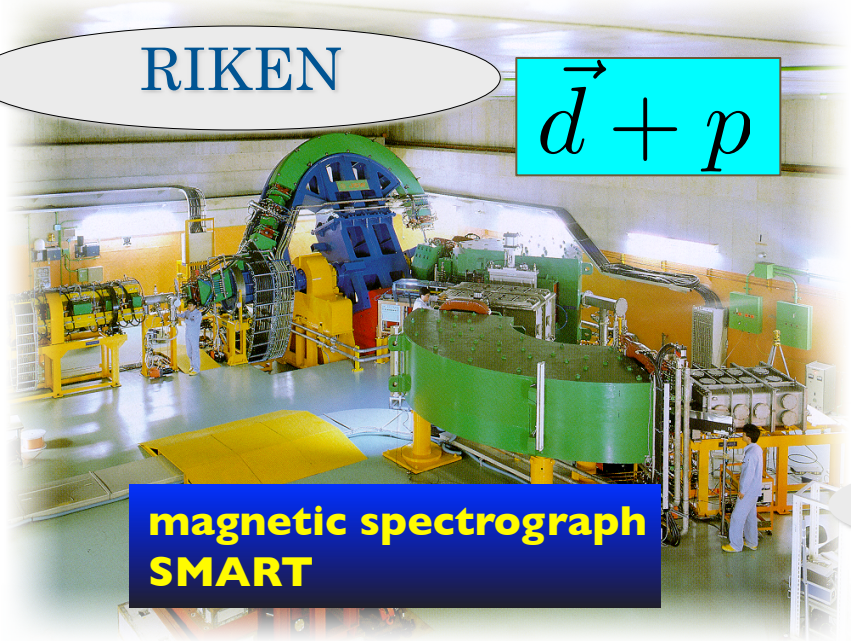

**Grand Raiden & LAS**

## RCNP

# Facilities

RIKEN

$\vec{d} + p$



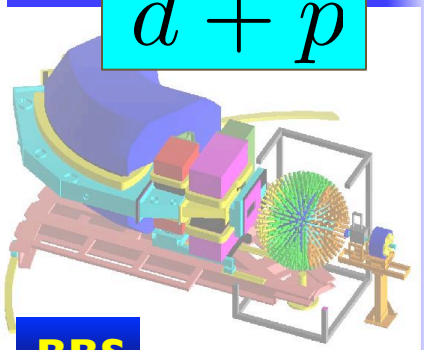
magnetic spectrograph
SMART

BINA
& SALAD

KVI

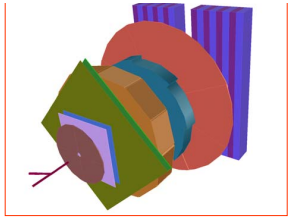
$\vec{p} + d$

$\vec{d} + p$

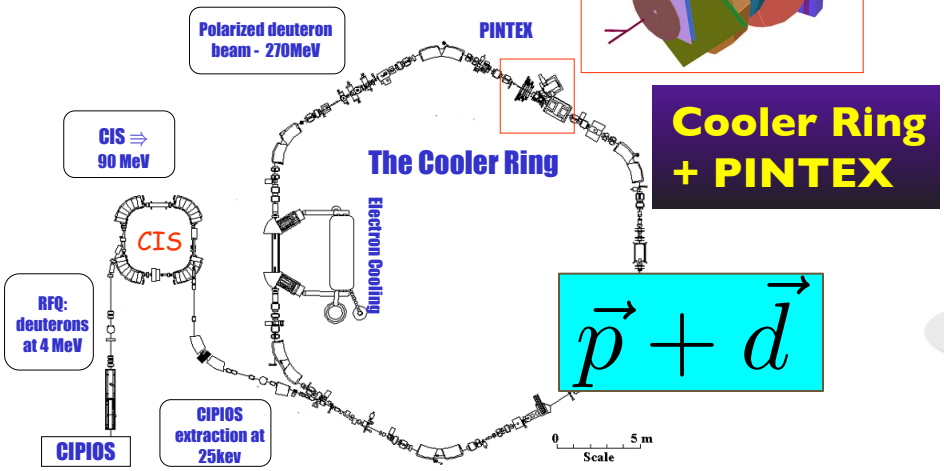


BBS

IUCF



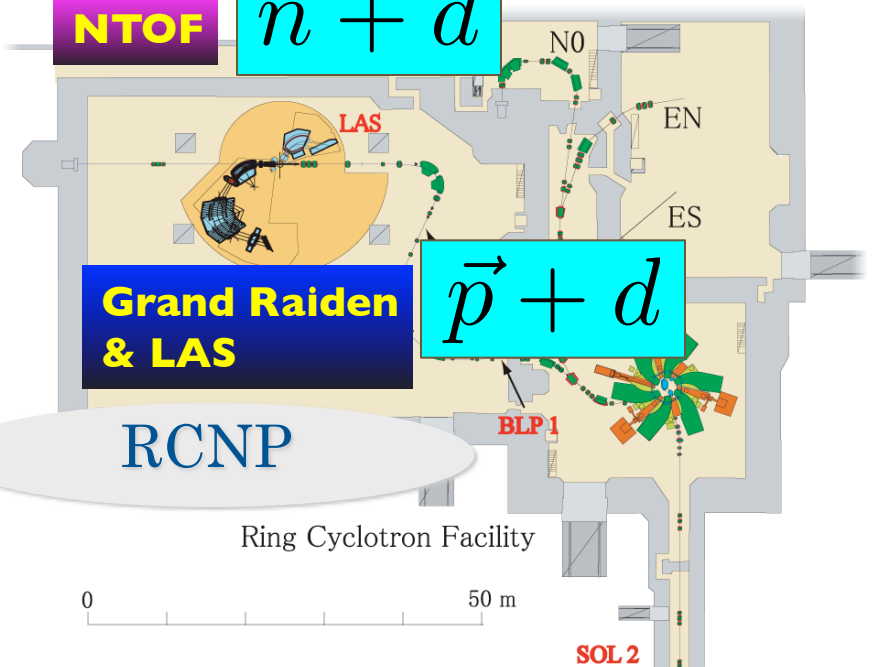
Cooler Ring
+ PINTEX




$\vec{p} + \vec{d}$

NTOF

$\vec{n} + d$




Grand Raiden
& LAS

$\vec{p} + d$

RCNP

# How to attack 3NF - 1st Step - d-p Elastic Scattering at 135 MeV/nucleon @ RIKEN Accelerator Research Facility (RARF)

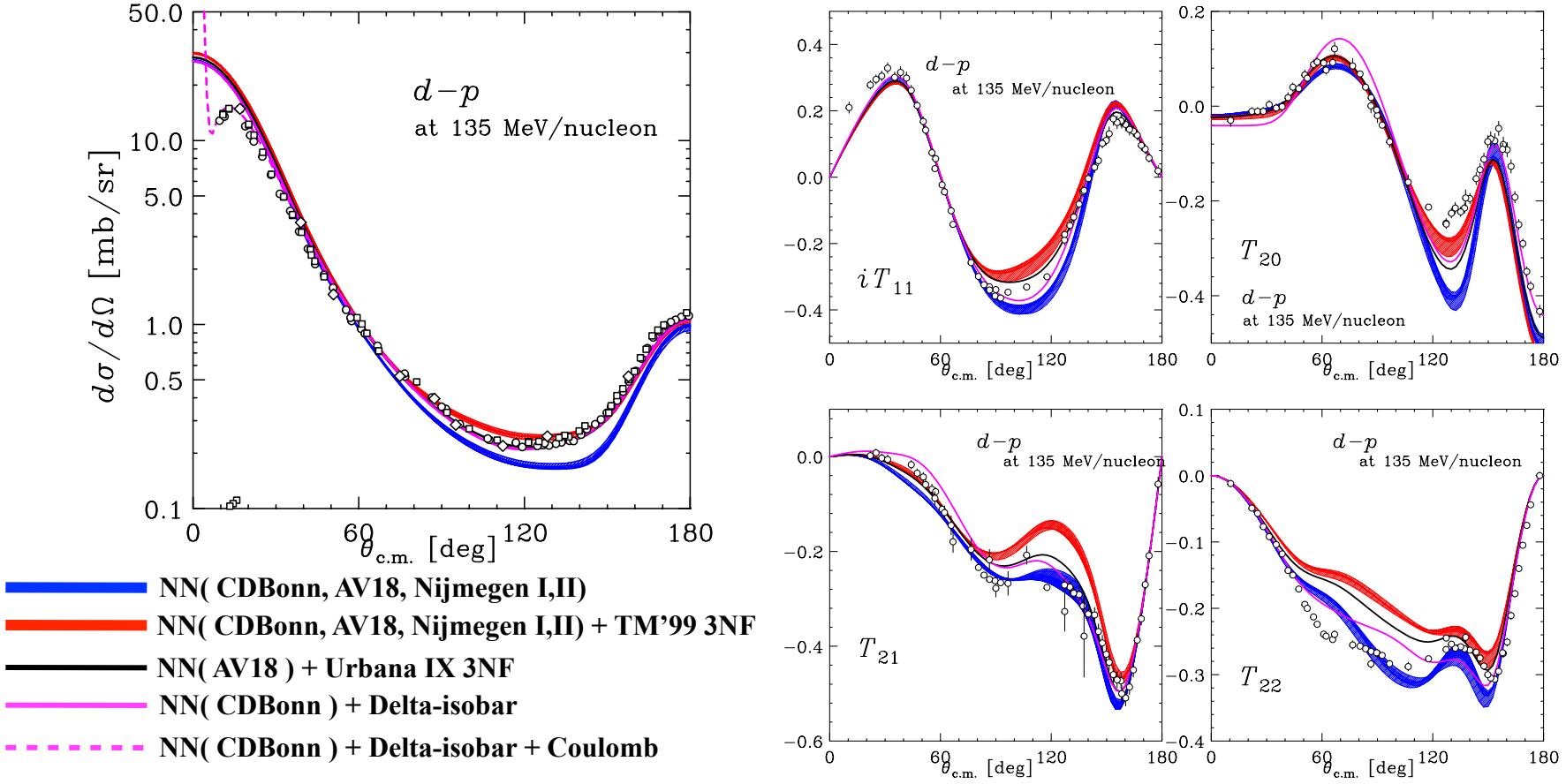
**Cross Section** : Good description by 2π-3NF

First Clear Signature of 3NFs in 3N Continuum

**Spin Observables** : Insufficient descriptions by 2π-3NF

Defects of 3NF in Spin parts ??

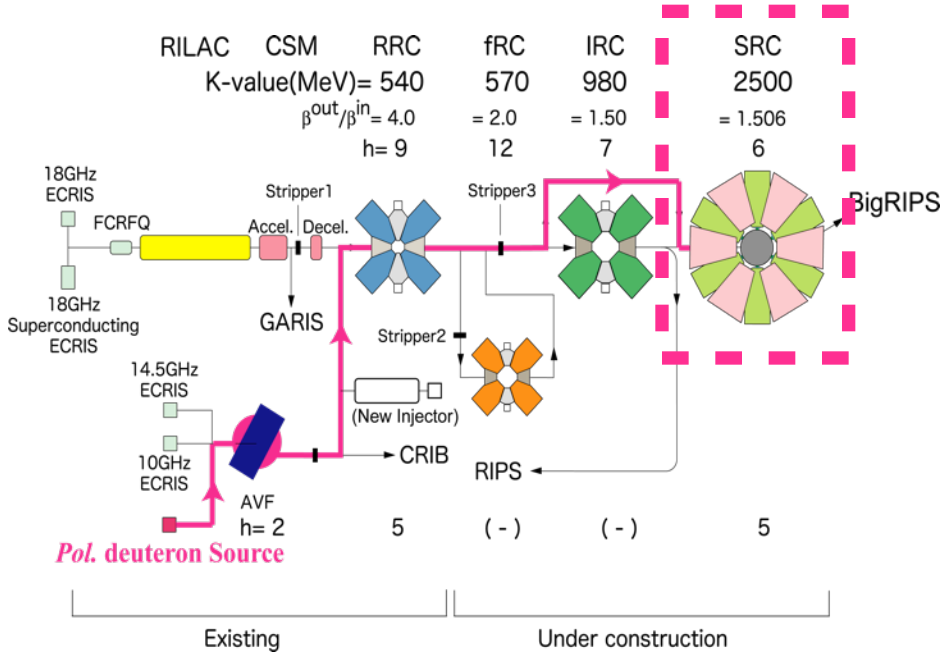
K. S. et al., Phys. Rev. C 65, 034003 (2002).
K. S. et al., Phys. Rev. Lett. 95, 162301 (2005).



# How to attack 3NF – Next Step –
# Few Nucleon Scattering with pol.d beams
# @ RIKEN RI Beam Factory (RIBF)

- **RARF : AVF+RRC**
  - **Incident energy of deuteron :**
    - **65 – 135 MeV/nucleon**

- **RIBF : AVF+RRC + SRC**
  - **Incident energy of deuteron :**
    - **170 - 440MeV/nucleon**




## *First Experiment at RIBF*

***dp* Elastic Scattering at 250 MeV/nucleon**

- **All deuteron analyzing powers**

$$A_y^d, A_{yy}, A_{xx}, A_{xz}(iT_{11}, T_{20}, T_{21}, T_{22})$$

- **Wide Angular Range**

$$\theta_{\mathrm{c.m.}} = 35^\circ - 160^\circ$$

- **High accuracy**

## *Go to higher energies*

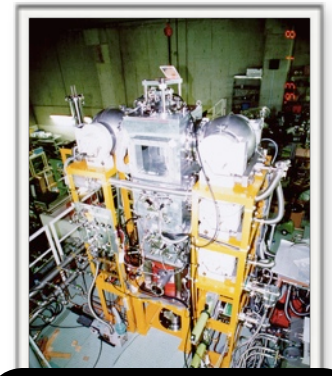
- Effects of 3NFs are relatively enhanced.
- Theory : harder

## *Polarized Deuterons*

- rich set of spin observables

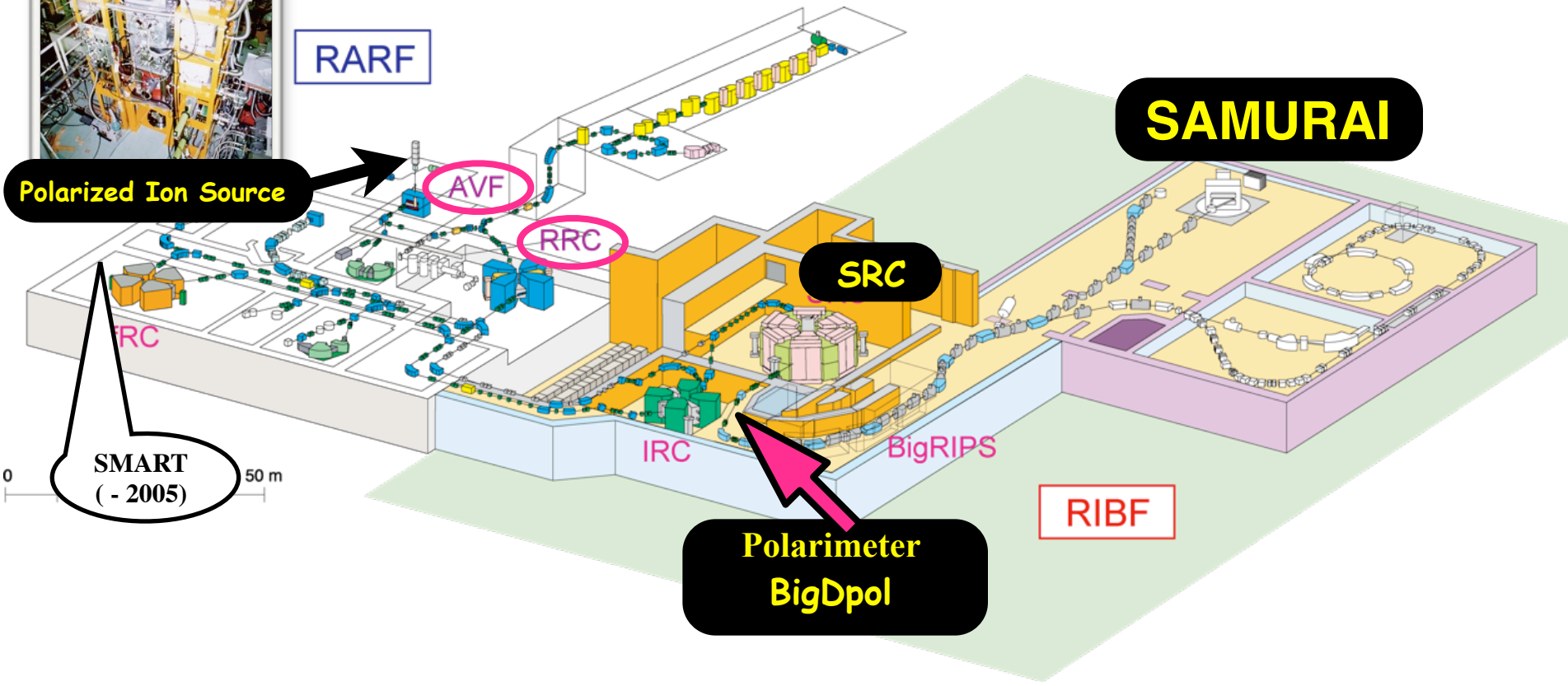
# *RIKEN RI Beam Factory (RIBF)*

- **First commissioning/experiment** of pol.d beams at RIBF was performed with the **polarimeter BigDpol** **in April, 2009**.
- **Polarized *d* beam** was accelerated by the AVF+RRC+ **the new cyclotron SRC** up to **250 MeV/nucleon**.
- Spin axis of deuteron beam was rotated **prior to acceleration.**
- **Single turn extraction of beam was successfully obtained for all the cyclotrons.**



→ **Polarization amplitudes were maintained during acceleration.**
- **Beam Polarization : 80% of theoretical maximum values**

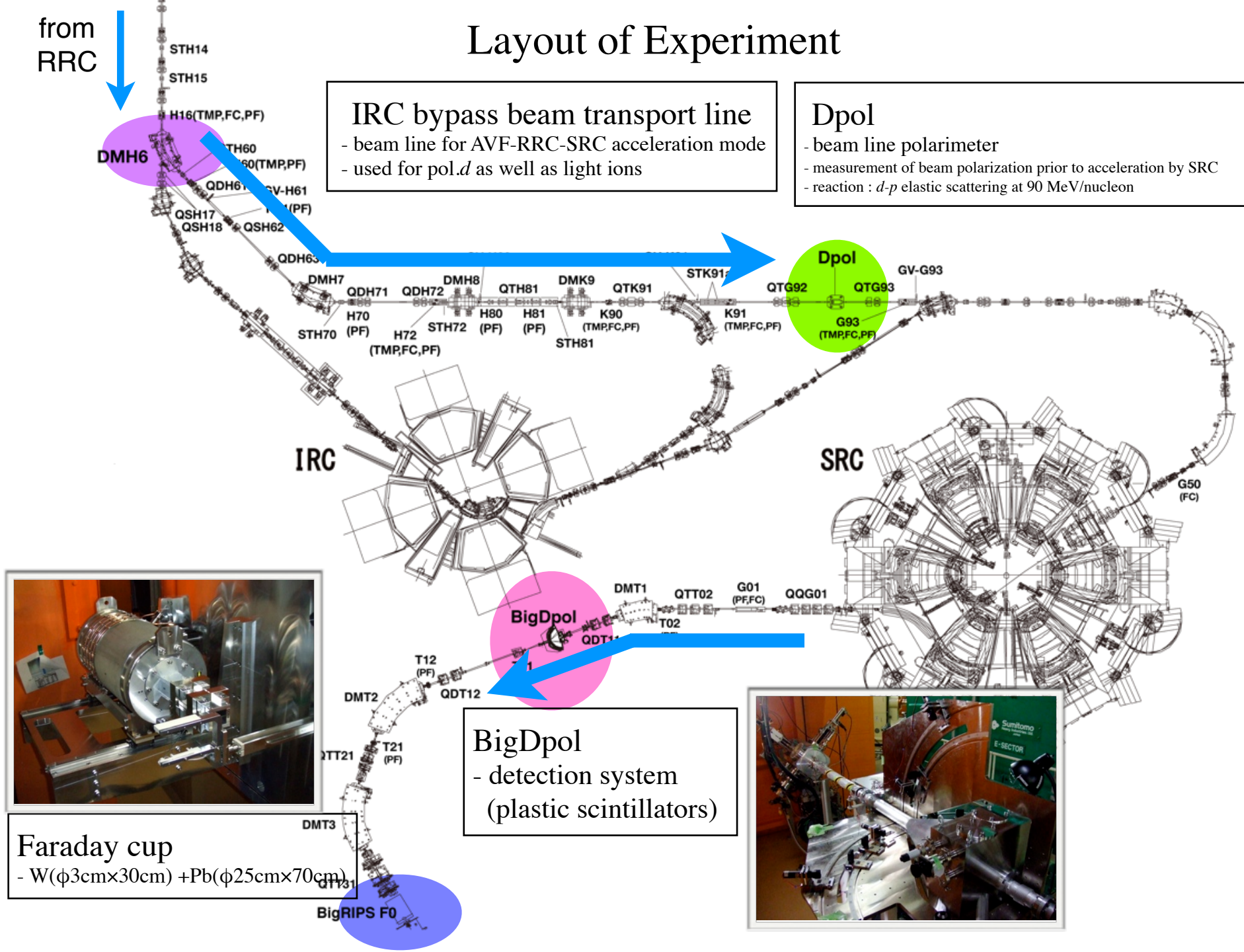
**Spin axis of polarized d beams is freely controlled !**



# Layout of Experiment

## IRC bypass beam transport line
- beam line for AVF-RRC-SRC acceleration mode
- used for pol.*d* as well as light ions

## Dpol
- beam line polarimeter
- measurement of beam polarization prior to acceleration by SRC
- reaction : *d*-*p* elastic scattering at 90 MeV/nucleon





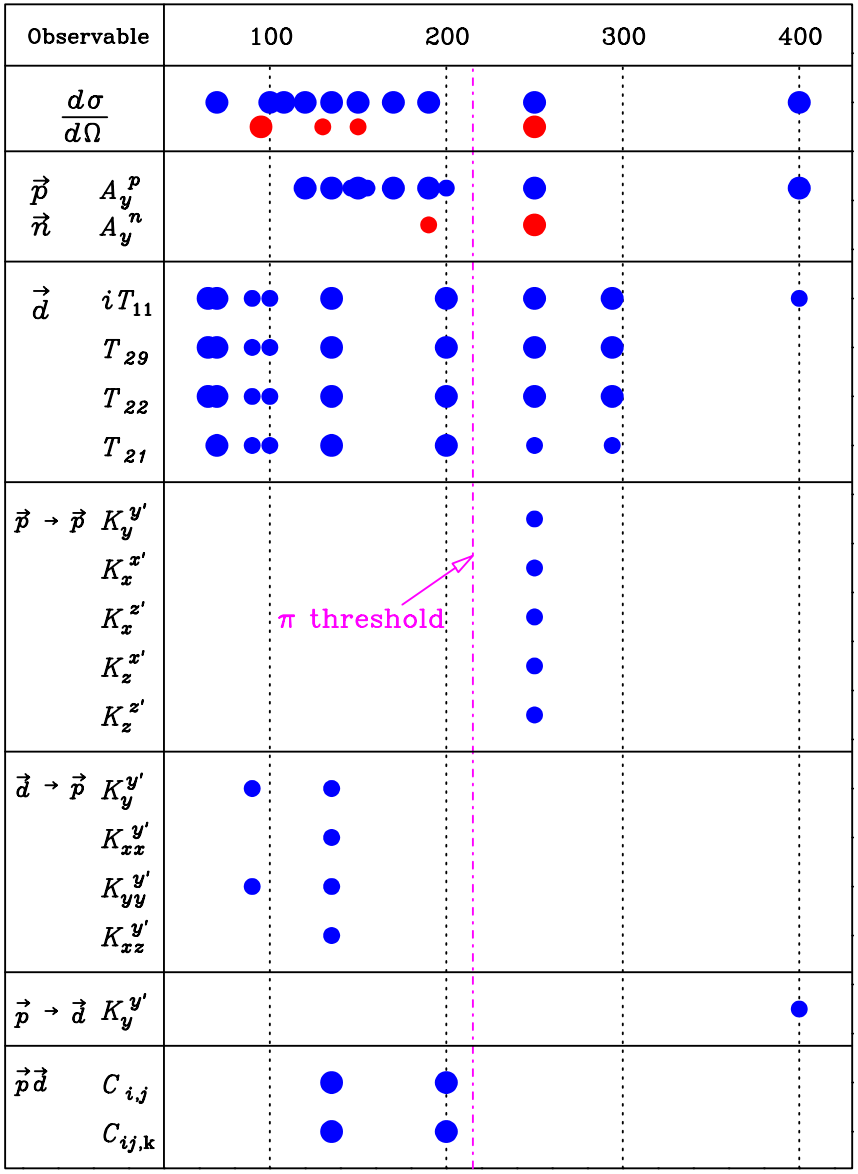

## Faraday cup
- W(ϕ3cm×30cm) +Pb(ϕ25cm×70cm)

## BigDpol
- detection system
  (plastic scintillators)

# Construction for pol. *d* beam Experiment at RIBF

# *Nd* Elastic Scattering Data at Intermediate Energies

$pd$ and $nd$ Elastic Scattering at 70–400 MeV/nucleon




~2012

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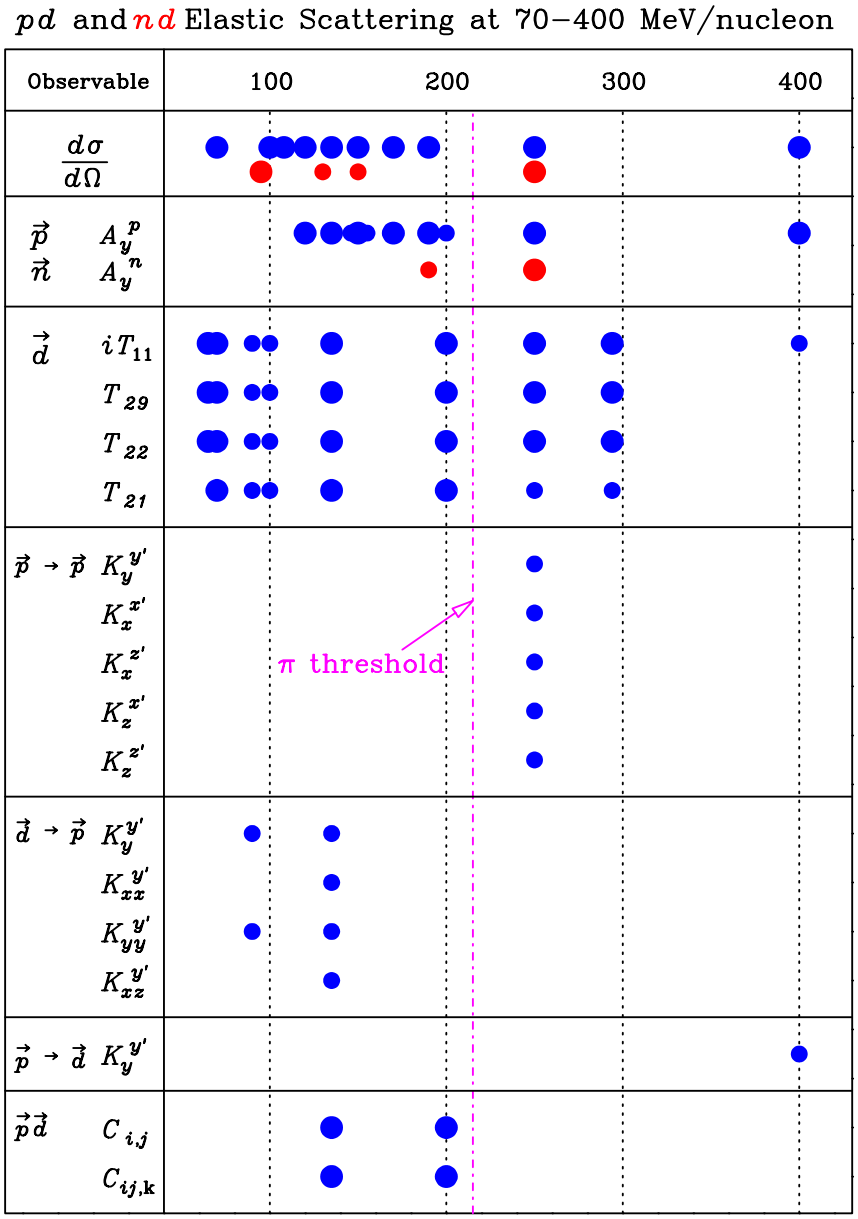
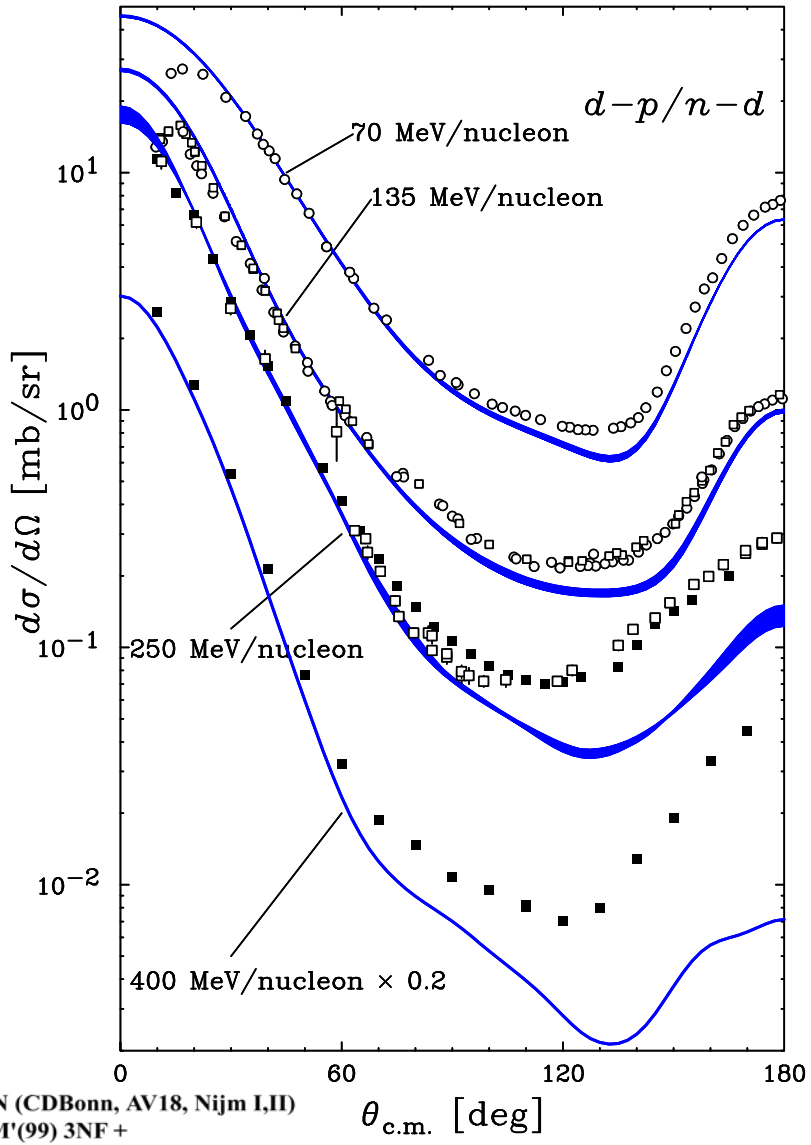



~2012

- **High precision data of**
  **$d\sigma/d\Omega$ & Spin Observables**
  **from RIKEN, RCNP, KVI, IUCF**

- **Energy dependent data**
  - ✓ **$d\sigma/d\Omega$**
  - ✓ **Proton Analyzing Power**
  - ✓ **Deuteron Analyzing Powers**

# Differential Cross Section at 70 - 400 MeV/nucleon




NN (CDBonn, AV18, Nijm I,II)
TM'(99) 3NF + NN(CD Bonn, AV18, Nijm I,II)
Urbana IX 3NF+AV18

- NN only
  - Large discrepancy in the backward region

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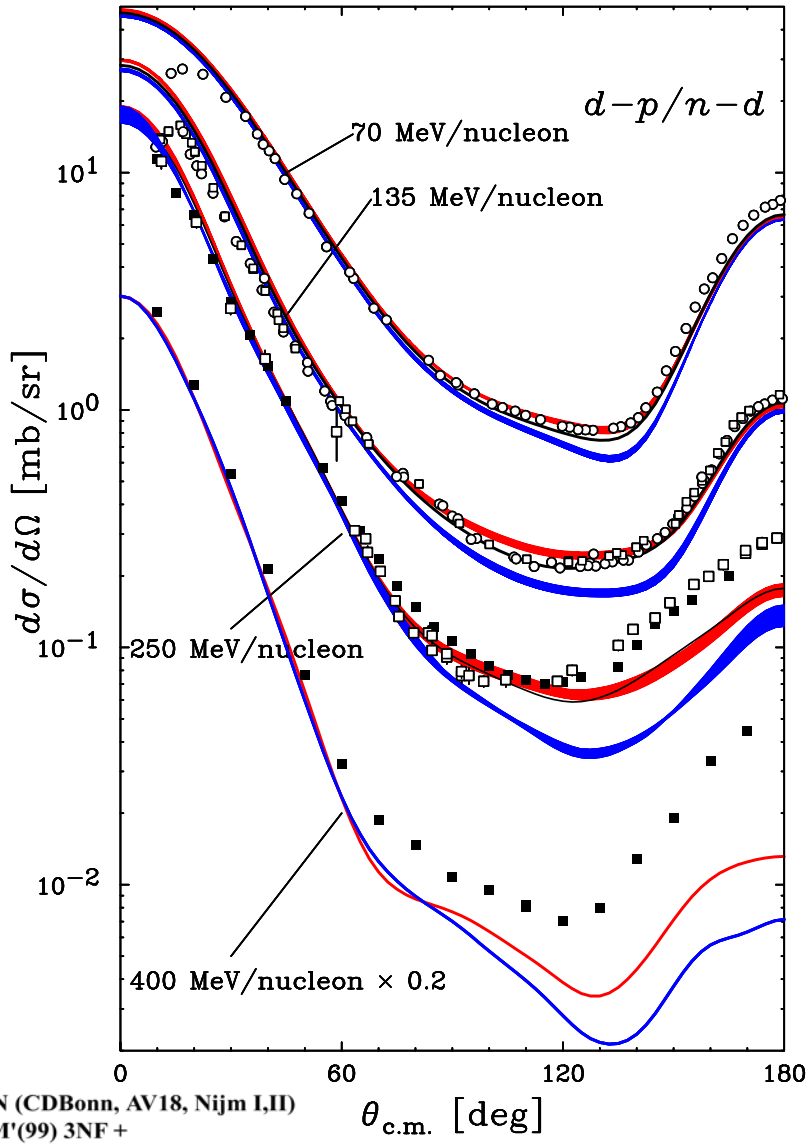


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- With $2\pi$-3NF ?
  - improve the agreement
  - not enough at very backward angles at higher energies

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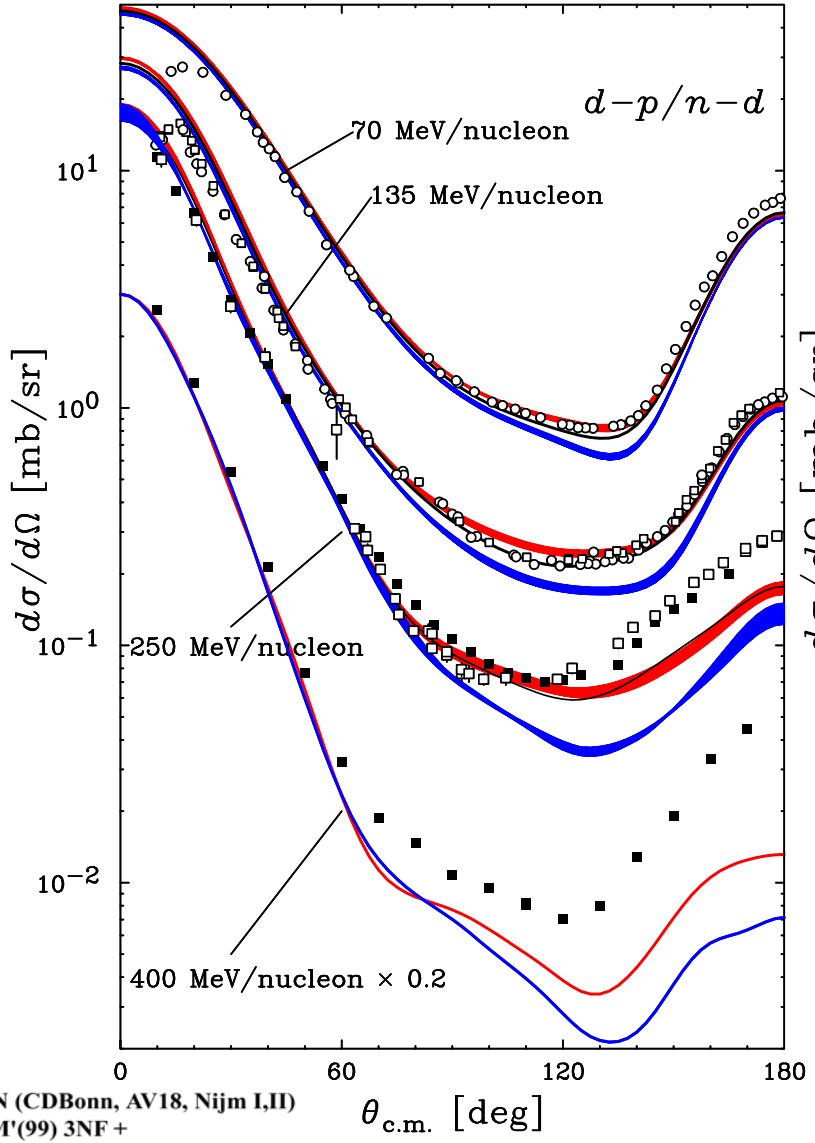
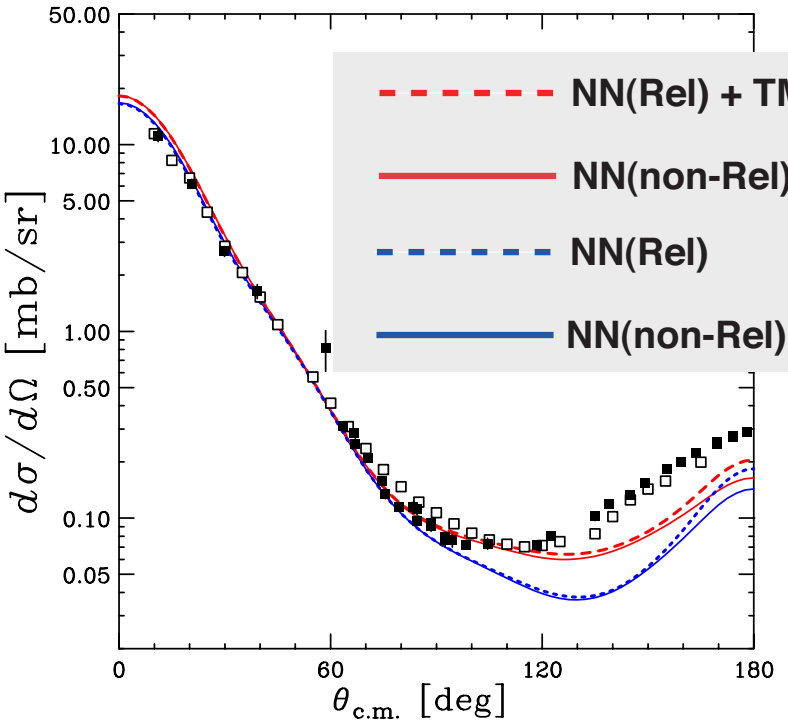



## Relativistic Faddeev Calculations with TM'99 3NF

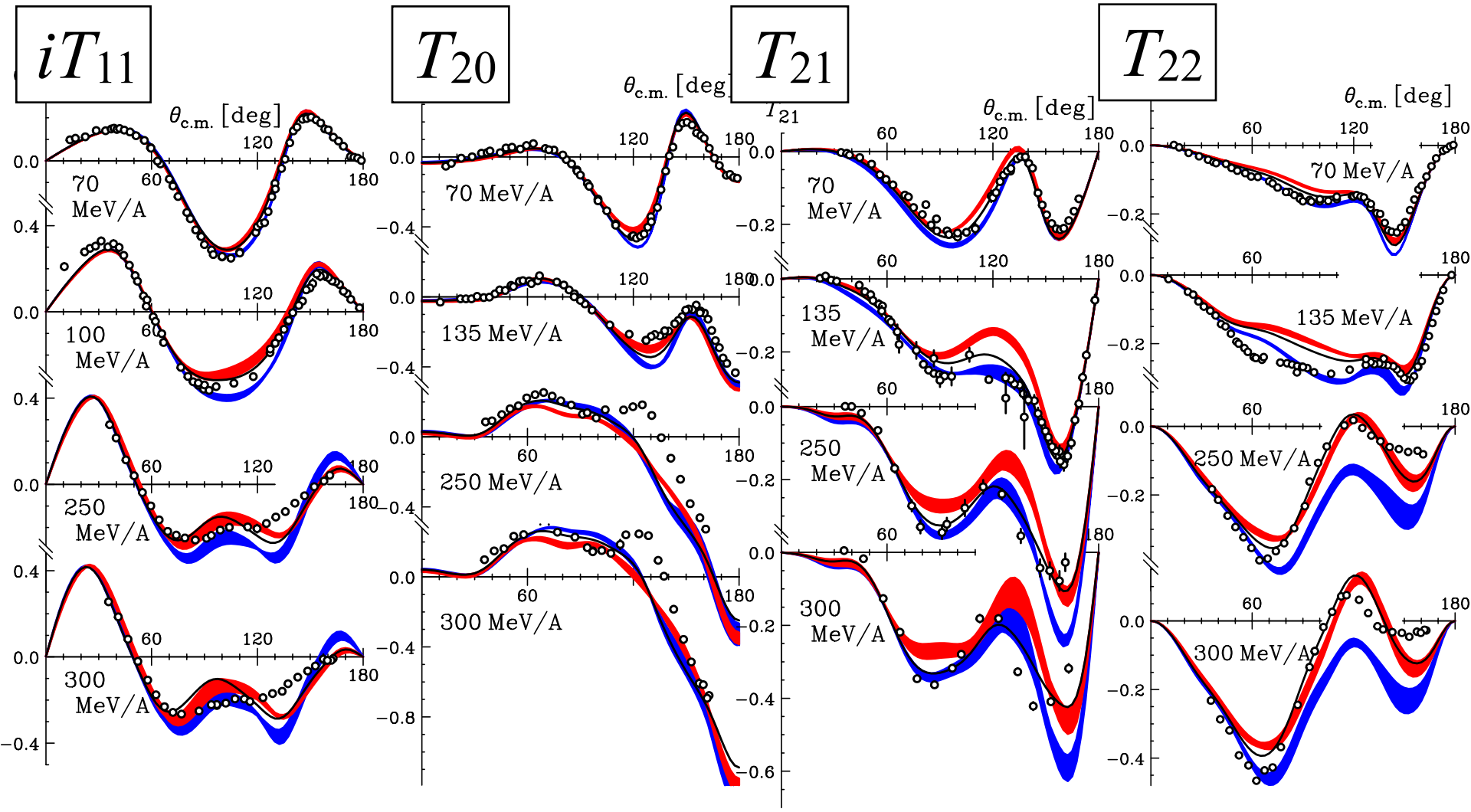
H. Witala et al, private communications

*pd/nd* @ 250 MeV




**Relativistic effects are visible at backward angles, but small.**

# Deuteron Analyzing Powers at 70 - 300 MeV/nucleon



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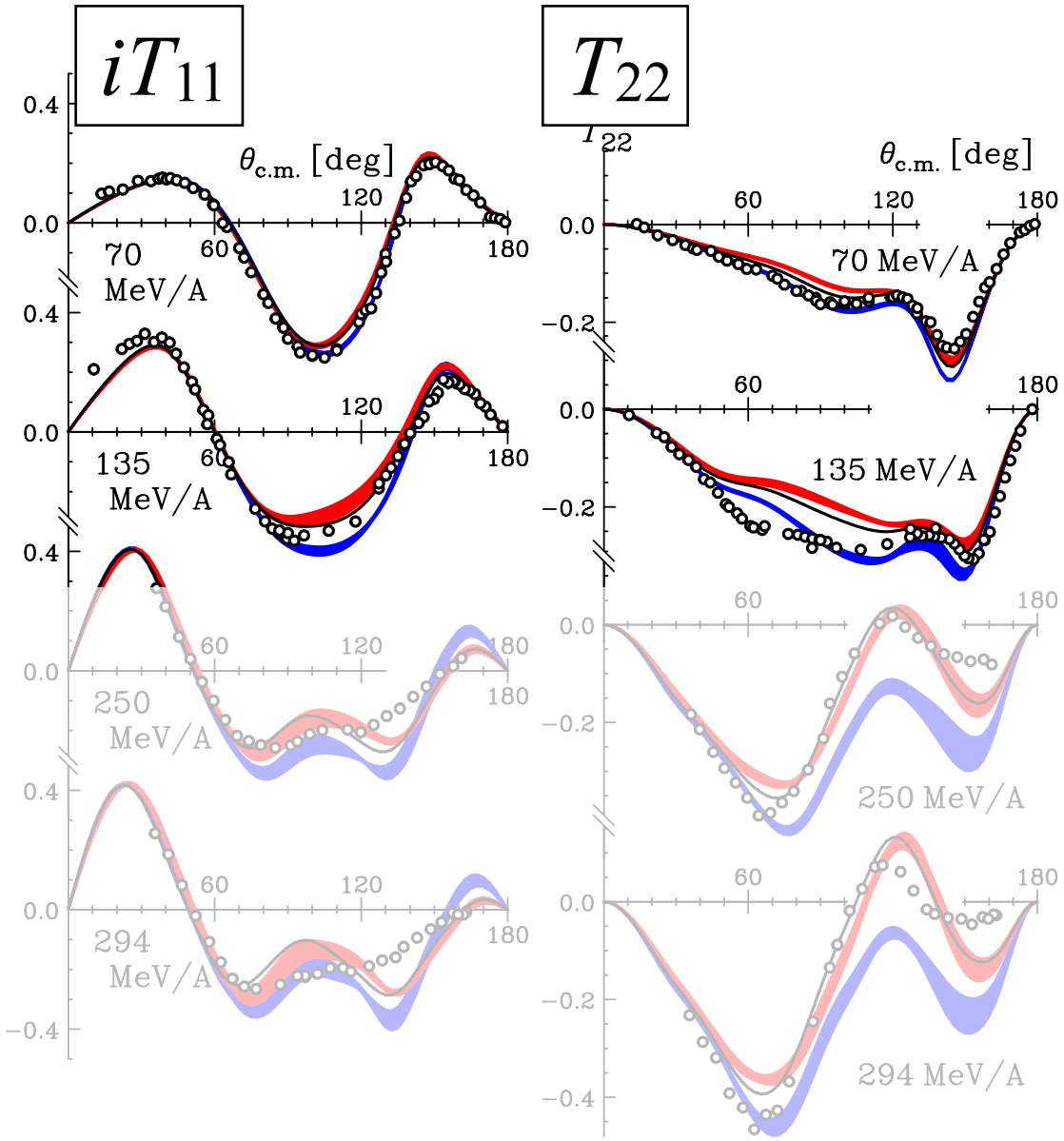


K.S. et al., Phys. Rev. C 83,061001 (2011)

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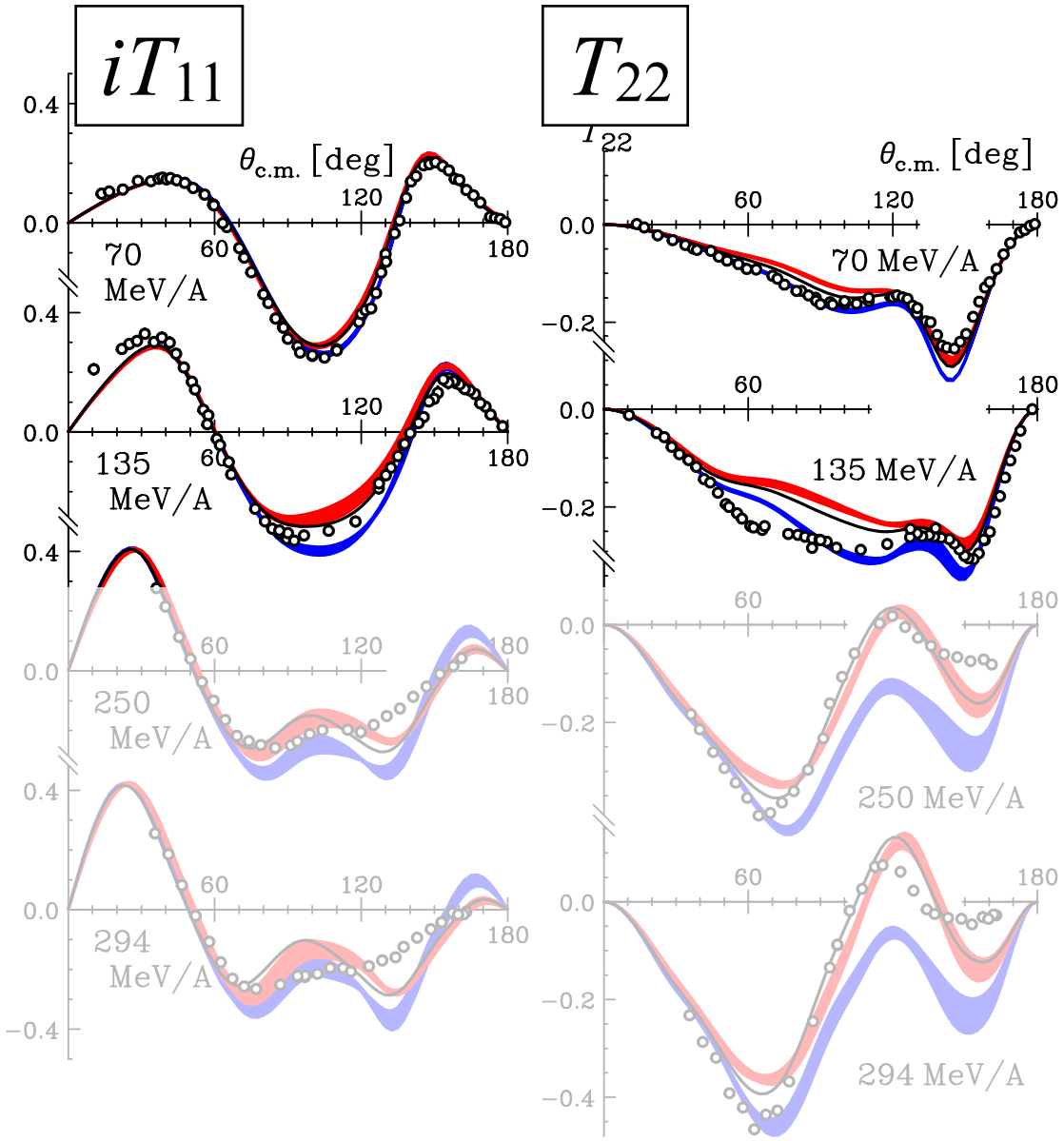


- NN only
  - Large discrepancy in the backward region
- + 2π3NF at ~ 100 MeV/A
  - results are NOT always similar to the cross section.

K.S. et al., Phys. Rev. C 83,061001 (2011)

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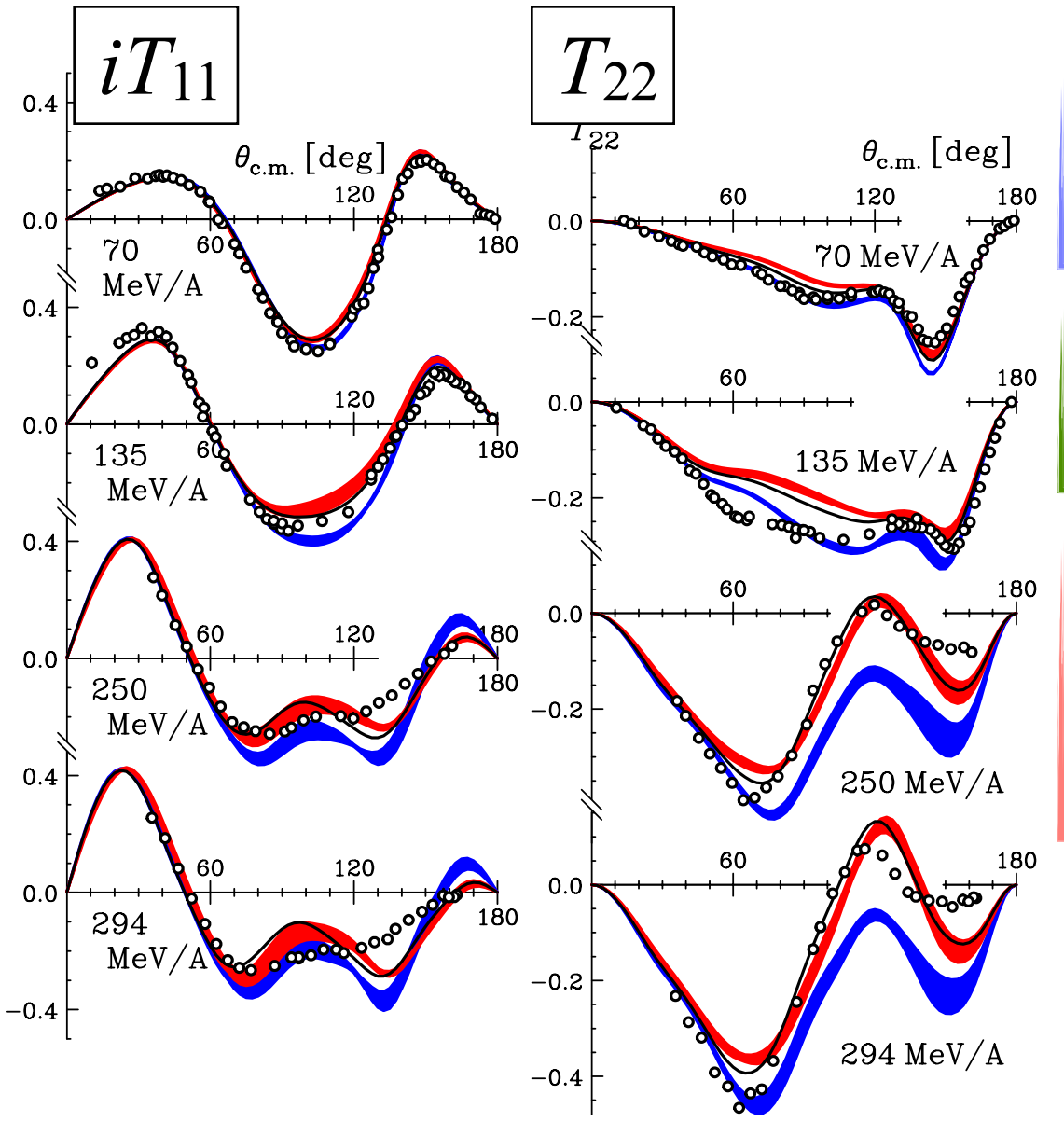



- NN only
  - Large discrepancy in the backward region
- + 2π3NF at ~ 100 MeV/A
  - results are NOT always similar to the cross section.
- + 2π3NF at ~ 250 MeV/A
  - improve the agreement
  - not enough at very backward angles

→similar to the cross section

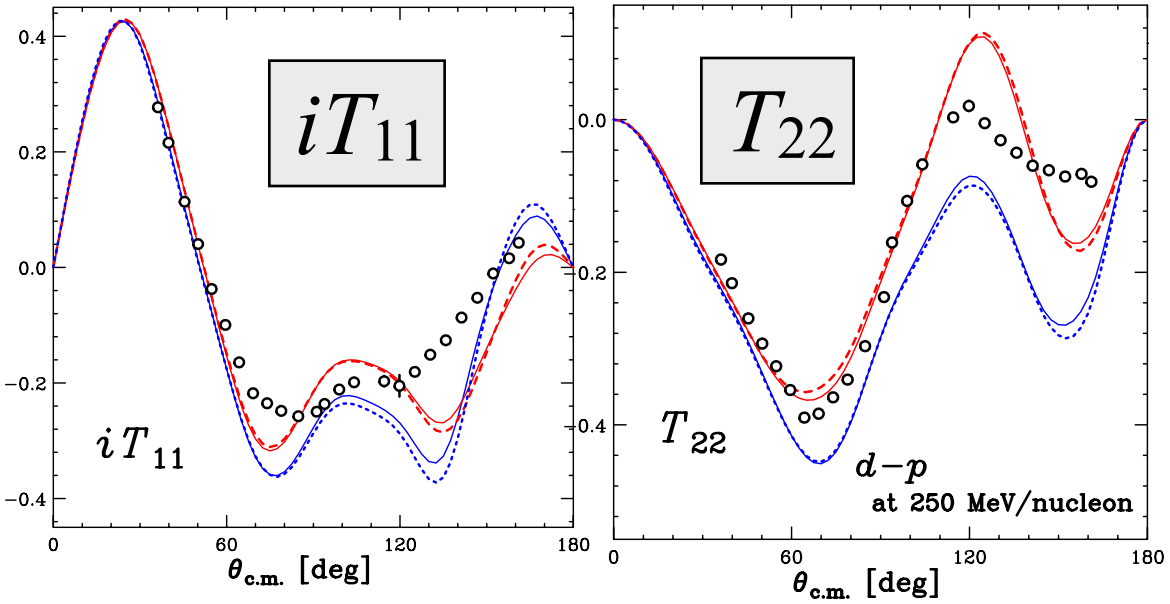
K.S. et al., Phys. Rev. C 83,061001 (2011)

# Deuteron Analyzing Powers

## Relativistic Faddeev Calculations with TM'99 3NF

H. Witala et al, private communications

### $dp$ @ 250 MeV




**Small relativistic effects**

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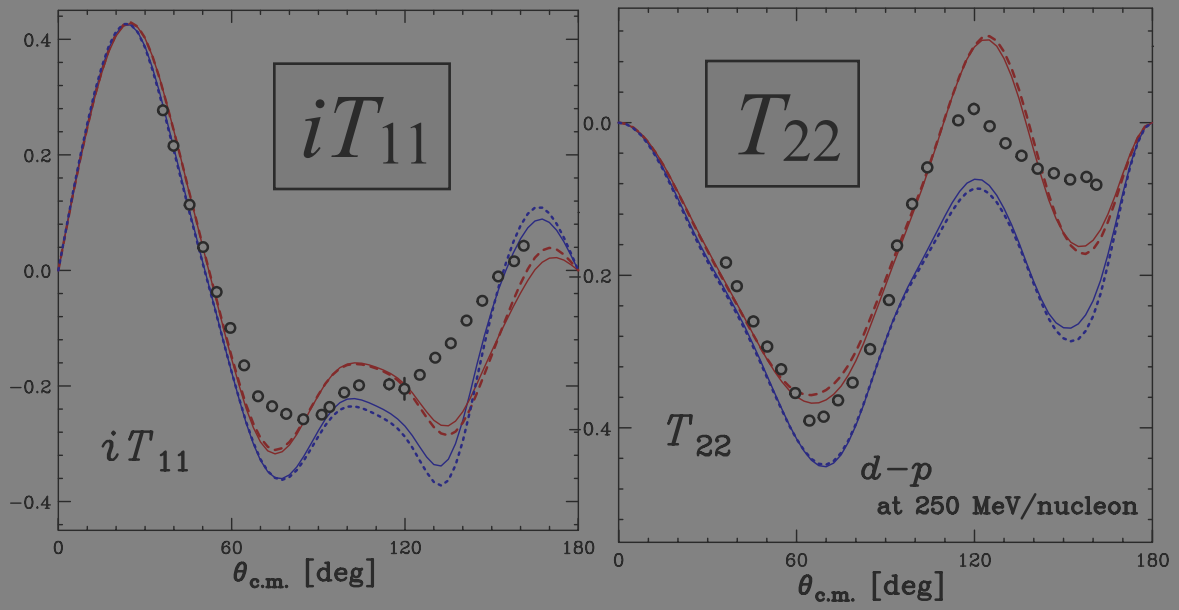



**Small relativistic effects**

# Deuteron Analyzing Powers

## Relativistic Faddeev Calculations with TM'99 3NF

H. Witala et al, private communications

*dp* @ 250 MeV

- **Around 100 MeV/nucleon**
  elastic scattering data are mostly explained by adding 2π3NF, (though there are some exceptions, e.g. $T_{22}$).

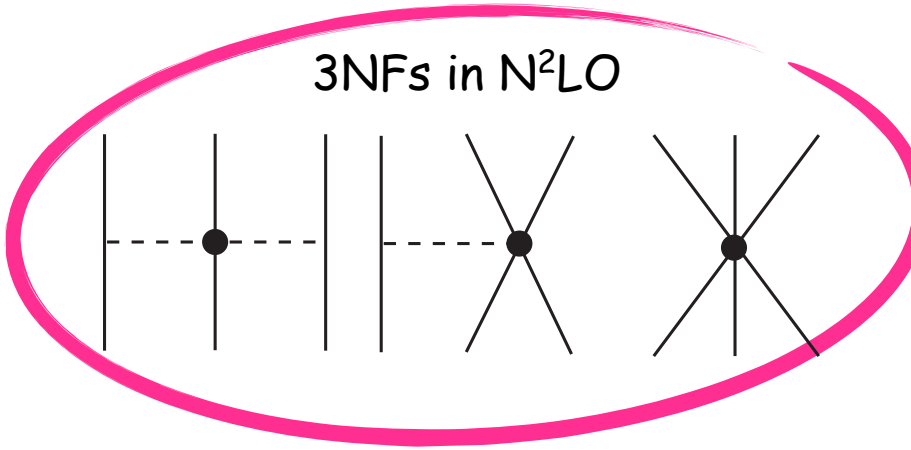
- **Serious discrepancies** exist at very backward angles at higher energies (250, 300 MeV/nucleon).

- **"What" we are missing ?**
  Components other than 2π3NF or relativistic effects; e.g. heavier meson exchange 3NFs .

# How does Chiral EFT pot. describe the Nd elastic scattering ?

Various types of 3NFs, including 2π3NF, appear in $N^2LO$, $N^3LO$.
Theory in Progress : up to $N^3LO$ (NN + NNN) for higher energies

So far calc. based on χEFT pot. is available below 100 MeV/nucleon.



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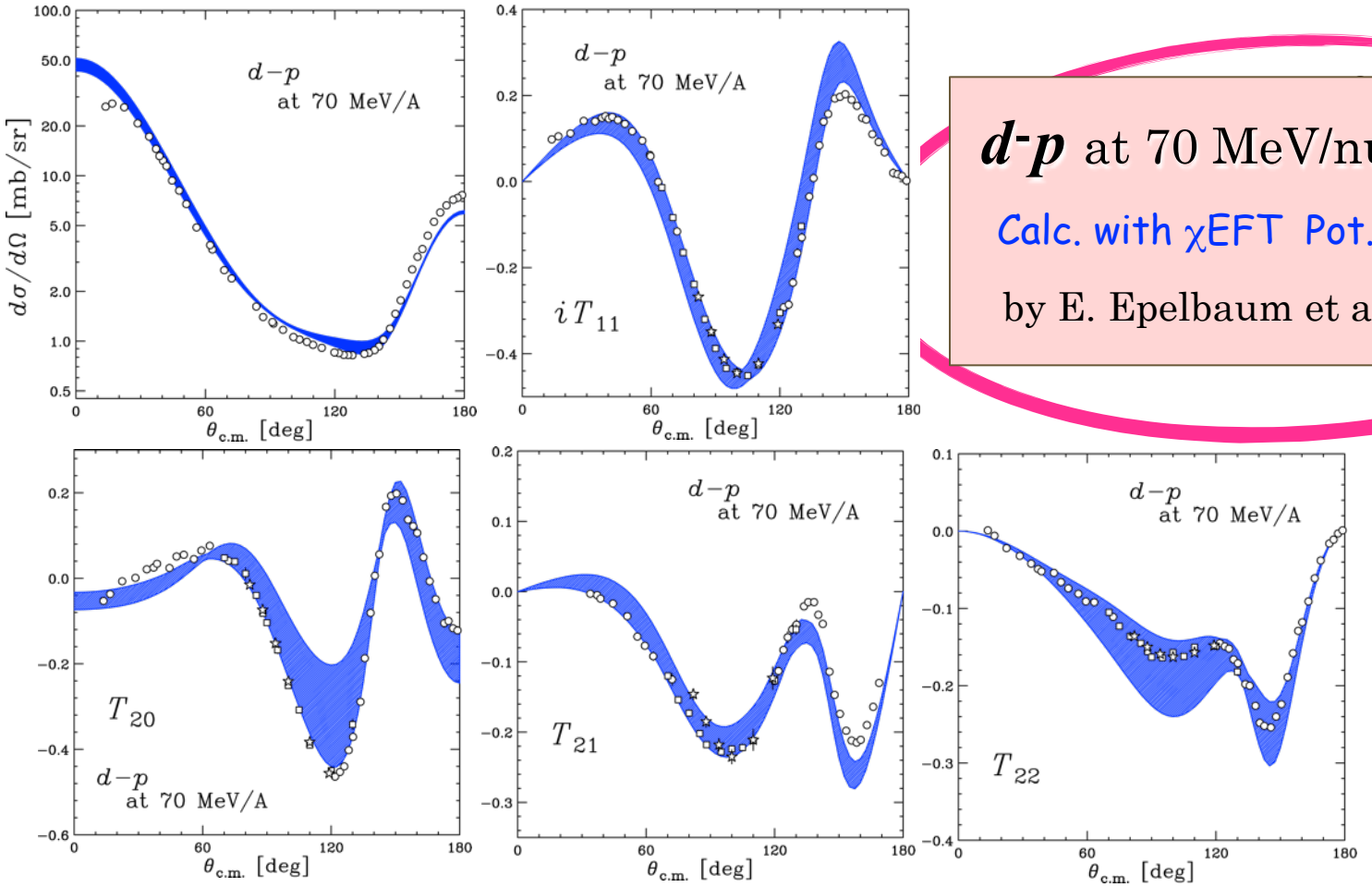
Various types of 3NFs, including 2π3NF, appear in $N^2LO$, $N^3LO$.
Theory in Progress : up to $N^3LO$ (NN + NNN) for higher energies

So far calc. based on χEFT pot. is available below 100 MeV/nucleon.




***d-p*** at 70 MeV/nucleon

Calc. with χEFT Pot. (N2LO)

by E. Epelbaum et al.

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**Precise data of $d\sigma/d\Omega$ and many spin observables at 65 - 300 MeV/nucleon**

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## Next Step

**Energy Dependence for Pol. Transfer and /or Spin Correlation Coefficients for Elastic Nd Scattering : Natural extension of 3NF study in Elastic scatt.**

**Nd Breakup Experiments : Study of Relativistic Effects**

**Four Nucleon Scattering : from Few to Many & Iso-spin dependence**

# RIBF pol.d beam experiment Gr. (2009～)

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Thank you very much.